Analysis of the wind effects on Urban Heat Islands in the city of Manchester, UK

A dissertation submitted to The University of Manchester for the degree of Master of Science in Environmental Sciences, Policy and Management, MESPOM in The Faculty of Engineering and Physical Sciences

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Glossary of terms[*]

- **Absorption –** The process by which incident radiant energy is retained by a substance.
- **Adiabatic process**- a thermodynamic change of state of a system in which there is no transfer of heat or mass across the boundaries of the system. Compression always results in warming, expansion in cooling.
- **Advection-** primarily used to describe predominantly horizontal motion in the atmosphere.
- **Albedo-** the ratio of the amount of radiation reflected by a body to the amount incident upon it. Usage varies but there 'radiation' is restricted to the short wave lengths (0.15-3.0 μm).
- **Ambient air –** the air of the surrounding environment.
- **Boundary layer** – a general term used for the layer that is adjacent to the surface.
- **Conduction-** the transfer of energy in a substance by means of molecular motions without any net external motion.
- **Convection-**mass motion within a fluid resulting in transport and mixing of properties for example energy and mass. This usually occurs vertically in the atmosphere.
- **Climate Change**- Climate change refers to a change in the state of the climate that can be identified (e.g. using statistical tests) by changes in the mean and/ or the variability of its properties, and that persists for an extended period, typically decades or longer. Climate change may be due to natural internal processes or external forcings, or to persistent anthropogenic changes in the composition of the atmosphere or in land use.
- **Diurnal**-daily
- **Eddy-**circulation in the lee of an obstacle brought about by pressure irregularities.
- **Emissivity**-the ratio of the total radiant energy emitted per unit time per unit area of a surface at a specified wavelength and temperature .

[*] Definitions are based on those of Oke (1978) and IPCC (2007).

- **Flux**- rate of flow of some quantity.
- **Fossil fuels -**Carbon-based fuels from fossil hydrocarbon deposits, including coal, peat, oil and natural gas.
- **Global warming-**Global warming refers to the gradual increase, observed or projected, in global surface temperature, as one of the consequences of radiative forcing caused by anthropogenic emissions.
- **Greenhouse effect-**Greenhouse gases effectively absorb infrared radiation, emitted by the Earth's surface, by the atmosphere itself due to the same gases and by clouds. Atmospheric radiation is emitted to all sides, including downward to the Earth's surface. Thus, greenhouse gases trap heat within the surface-troposphere system. This is called the greenhouse effect.
- **Greenhouse gases -** Greenhouse gases are those gaseous constituents of the atmosphere, both natural and anthropogenic, that absorb and emit radiation at specific wavelengths within the spectrum of infrared radiation emitted by the Earth's surface, the atmosphere and clouds. This property causes the greenhouse effect. Water vapour (H2O), carbon dioxide (CO2), nitrous oxide (N2O), methane (CH4) and ozone (O3) are the primary greenhouse gases in the earth's atmosphere.
- **Heat capacity**-the ratio of the heat absorbed or released by a system to the corresponding temperature rise or fall.
- **Inversion**-a departure from the usual decrease with height of an atmospheric property. Most commonly refers to a temperature inversion when temperatures increase.
- **Mitigation-** Technological change and substitution that reduce resource inputs and emissions per unit of output. Although several social, economic and technological policies would produce an emission reduction, with respect to climate change, mitigation means implementing policies to reduce GHG emissions and enhance sinks.
- **Sensible heat-**that heat energy that can be sensed by measuring instruments like thermometers etc.

- **Turbulence-**a state of fluid flow in which the velocities exhibit irregular and random fluctuations, these transfer heat at rays far above the normal**.**

List of Abbreviations

AR4	Fourth Assessment Report of the United Nations
BLHI	Boundary Layer Heat Island
CLHI	Canopy Layer Heat Island
DEFR	Department for Environment, Food and Rural Affairs A
EBMs	Energy Balance Models
EPSRC	Engineering and Physical Sciences Research Council
GARP	Global Atmospheric Research Program
GCMs	Three-dimensional General Circulation Models
ICSU	International Council on Science
IPCC	Inter governmental Panel on Climate Change
RCMs	One-dimensional Radiative-Convective Models
SCORCHIO	Sustainable Cities: Options for Responding to Climate cHange Impacts and Outcomes
SDMs	Two-dimensional Statistical-Dynamical Models
SHI	Surface Heat Island
U. N	United Nations
WCRP	World Climate Programme
WMO	World Meteorological Organization

Abstract

Global warming is scientifically documented across the world and is estimated to worsen in the coming decades. Given the uncertainties and challenges that lay in predicting climatic changes for their occurrence, intensity and impacts, scientists favour the development of improved prediction models and the use of multiple models to better anticipate future risks.

Urban Heat Island effects i.e. the urban areas being much warmer than their surrounding rural areas, are increasingly becoming a norm in mega-cities. Anthropogenic activities attributed to ‘development’ have been identified as main causes for Urban Heat Island, particularly changes in the biophysical characteristics of urban space and rapid growth in built environments. Urban heat island effects will only worsen when coupled with global warming impacts.

Built structures obstruct wind flow and alter wind speeds affecting surface and air temperatures. The current thesis analyses the impact of wind speeds and roughness lengths on urban surface temperatures and hence on Urban Heat Island, in Greater Manchester. The study used Tso Energy Balance Model (1990; 1991) for analysis. Model runs with varying wind speeds and roughness lengths calculated surface temperatures for model sensitivity. To verify model performance, the model output data was compared to real data obtained from Meteorological office, UK.

The model findings confirm that both wind speed and roughness length inversely affect urban surface temperatures in Greater Manchester, UK. The model was efficient in estimating surface temperatures for urban conditions. It is then recommended that such studies be duplicated at multiple locations as well as over time to substantiate the study findings. However, there were large discrepancies in modeling data and observed data values for rural conditions. Reasons for this need further exploration.

Modeling offers a pragmatic tool to anticipate future risk scenarios for Urban Heat Island effects. They generate useful information and evidence that may help urban planners and policy makers to mitigate Urban Heat Island impacts through adaptations. Such efforts should to be duplicated globally.

Declaration of Original Work

To whomsoever it may concern

This thesis is the result of independent investigation. Where my work is indebted to the work of others, I have made appropriate acknowledgements.

I declare that this study has not already been accepted for any other degree nor is it currently being submitted in candidature for any other degree.

Neelambari Phalkey
23rd May 2008

Neelambari Phalkey
23rd May 2008

Chapter 1
Background Introduction

Several programs on numerical modeling have been initiated to understand the evolution of global climate system since 1960s. In the 1970's, the study of global climate system gained shape within observational programs of the World Meteorological Organization (WMO) and the International Council on Science (ICSU). (Houghton et al., 1984) Climatology has evolved rapidly ever since into the current Global Atmospheric Research Program (GARP) and the World Climate Research Programme (WCRP) in Geneva. (Houghton et al., 1984)

1.1 Climate change and global warming

Global rise in temperatures is by and large the single most apparent climate change phenomenon we observe. "Global warming refers to the gradual increase- observed or projected, in global surface temperature, as one of the consequences of radiative forcing caused by anthropogenic emissions." (IPCC, 2007) The main cause of global warming is the increased concentrations of green house gases like methane, ozone, particularly carbon dioxide (from the combustion of fossil fuels) and water vapour (IPCC, 2007).

Solar radiation that reaches the surface of the Earth is partly absorbed and the rest is radiated back to the atmosphere as long wave radiation. The film of green house gases act like a plate that reflects the heat energy back, which otherwise would have been lost in the atmosphere. IPCC (2007) The green house emissions add to the energy of the long wave radiation and accelerates the warming up of the atmosphere. (Houghton, 2004) Worldwide energy consumption coupled with increasing population especially in urban areas has exponentially increased the additional energy input by emissions and pollution. Continued greenhouse gas emissions at or above current rates would induce further warming in the global climate system much larger than those observed during the 20th Century. (IPCC, 2007; Hadley Centre, 2006)

Scientific evidence has shown that temperatures are soaring in all given seasons across the globe. The temperatures are estimated to rise further, proportional to the increase in

green house gases. (IPCC, 2007) The Fourth Assessment Report (AR4) of the United Nations Intergovernmental Panel on Climate Change (IPCC), predicts that for high emission scenarios the temperature will rise between 1.1°C and 6.4°C by 2100.
The graph in Figure: 1 represents the trends in global average temperatures.

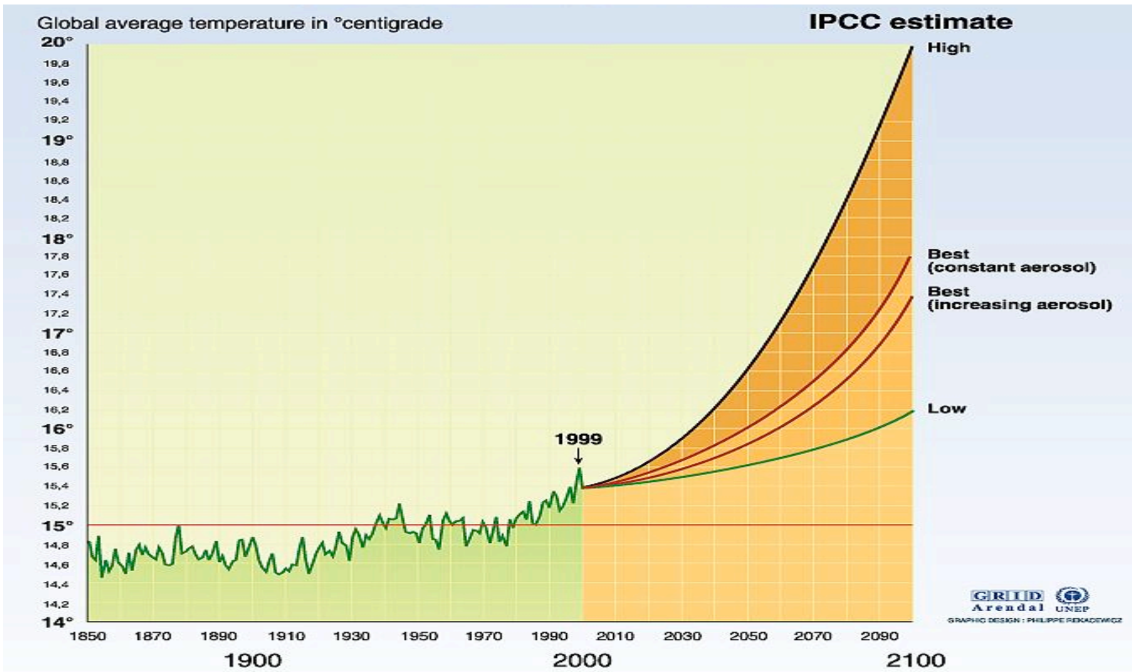

Figure 1: Trends in global average temperatures
Source: http://www.grida.no/climate/vital/graphics/large/22.jpg

Why does it matter if the global temperature rises?
The effects of rising global temperatures are widespread and include but are not limited to the following (Fourth Assessment Report of the IPCC 2007)

- Increased or decreased availability of water.
- Increase or decrease in food productivity and distribution.
- Increased coastal inundation due to rising sea levels.
- Higher risks of species extinction and changes in terrestrial biodiversity.
- Increased coral bleaching and mortality in marine ecosystems with changes in marine biodiversity.

- De-glaciation contributing to rising sea levels.
- Increased risks from changes in frequency and magnitude of extreme weather events such as heavy precipitation, tropical cyclones and droughts.
- Human health impacts including morbidity and mortality from heat waves, floods, droughts, increased burden of malnutrition, diarrhoeal, cardio-vascular and infectious diseases, facilitated transmission of vector borne diseases due to changes in distribution of disease vectors.

Given the unpredictability of occurrence and severity, the only pragmatic approach to combat climate changes lays in better adaptive strategies. To date most of our mitigation efforts have largely fallen short. (Houghton, 2004)

Changes in climate involve internal and external changes within the climate system. (Houghton, 2004) The climate system is driven by five major sub-systems: atmosphere, ocean, ice cover and land surface. Physical, chemical and biological processes take place within these complex subsystems which are inter-linked by mass, momentum and heat. (Met office, UK) These sub-systems may also be called *"Climate forcing."* (Barry et al., 2003) The Figure: 2 shows the interactions between each of the systems. The external changes that are generally observable include solar variability, astronomical effects and volcanic activity. The internal factors include natural variability mainly in the system feedback loop within the atmosphere, oceans and the surface of the earth. (Barry et al., 2003)

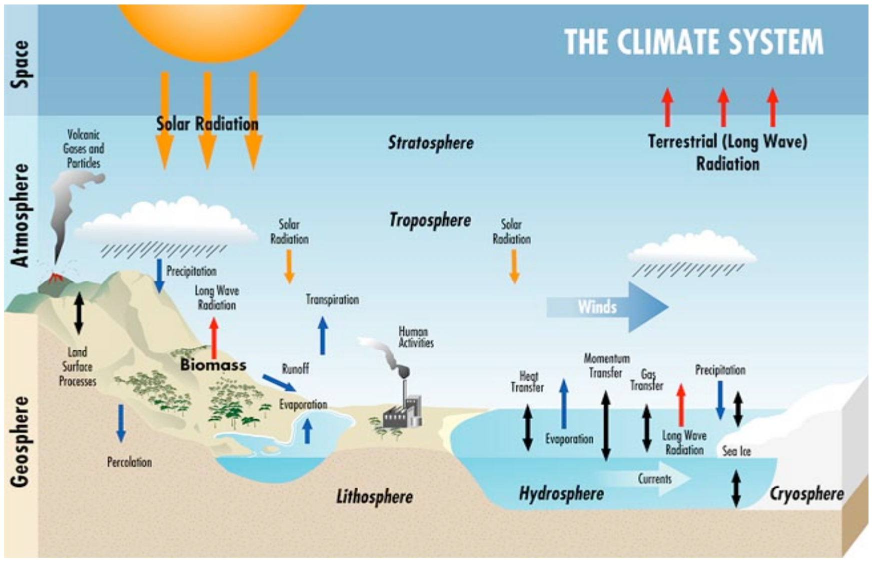

Figure 2: The climate System
Source: http://www.bom.gov.au/announcements/media_releases/ho/20030320d.jpg

It was in the twentieth century that human induced changes in the atmospheric composition due to green house gases became more pronounced on local and global scales particularly in urban areas. Cities are remarkably vulnerable to the effects of global warming due to compounded effects of pollution, over construction and lack of green spaces or water bodies. (Kalnay et al., 2003) Urbanization alters the character of space by the various biophysical changes it brings along in surface cover. (Whitford et al., 2001) The temperature in cities has been observed to be several degrees higher than in the countryside. (Wilby, 2003;Graves et al. 2001) Green house gas emissions will probably only augment the situation in the years to come.

Geiger et al., 2003 in his book *The climate near the ground* has discussed that urban climates had been changing even during the 1920s and the 1930s. He states that studies have been undertaken as early as in 1950s. T.J.Chandler studied the urban rural temperature differences at different times of the day around the city of London using an instrumented vehicle in the year 1930. (Geiger et al., 2003) Similar studies have been on-going for urban climates by mounting instruments on towers and tall buildings.

Helmut Landsberg has been working with historical data for cities in Europe and North America. (Barry et al., 2003) Tim Oke in Canada has done observational and modeling studies on urban energy budget and radiation and turbulence in urban canyons. (Barry et al., 2003)

There is an increasing trend of urbanization in the world today. Over 48% of the world's population lives in urban areas and over 4% in mega-cities as per the U.N records. (U.N, World Urbanization Prospects, 2003) Economic and commercial activities drive urban agglomeration at an unprecedented pace across developing and developed countries. Rapid and unregulated growth in urban areas has created unhealthy, dangerous and uncomfortable environments to work and live in. Today the need to understand the structure and functioning of urban climates is the greatest. To analyze the dynamic system of microclimates and the alterations within the urban systems it is useful to look at the *urban climates*.

1.2 Urban Climates

Urban canopy layer (UCL):

The urban canopy layer (UCL) is the layer of air closest to the surface in cities, extending upwards to approximately the mean building height. (Oke, 1995) The urban canopy layer consists of spaces between built structures such as buildings, walls, and the ground through which air can flow. The microclimates in these spaces depend on the angles of solar incidence and the angle –of – attack of the wind. (Oke, 1987) The variances in microclimates are additionally influenced by radiative, thermal and moisture retention characteristics of the construction materials used in the built environments, (Oke, 1995)

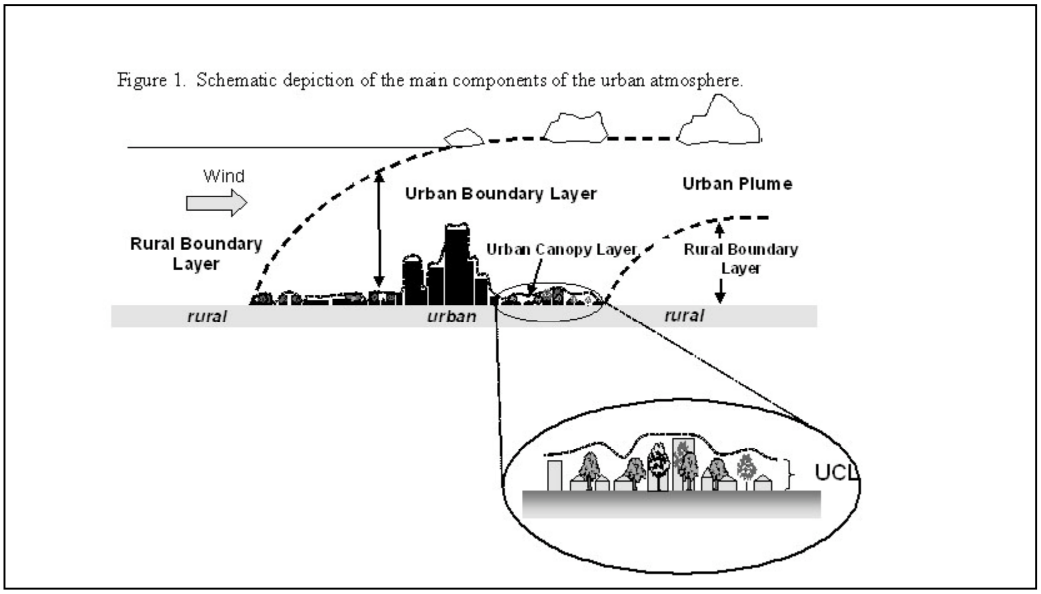

Figure 3: Components of urban atmosphere highlighting the urban canopy layer.
Source : www.actionbioscience.org/.../figures/voogt1.jpg

Canyon Geometry, is the ratio of the canyon width and height. It influences the micro-climates within the urban canopy layer by providing increased or decreased surface areas for reflection and re-absorption of short wave radiations and by altering wind speeds. Reduced sky view factor due to built surface areas also affects the climate inside the urban canopy layer. These variations get more pronounced after sunset and during the nights. (Wilby, 2003; Barry, 2006; and Oke, 1995) Thus, new complexities depending on the density, functions and design or geometry of the structures of the built environment gain importance in studying urban microclimates. (Barry et al., 2003)

Boundary layer climates or microclimates:

The urban boundary layer is the portion of the planetary boundary layer that lays above the urban canopy layer (See Figure: 3). (Oke, 1987) It may extend to 1 km or more by day and shrinks to a few hundred meters or less by night. (Voogt, 2006) Boundary layer is vulnerable to diurnal temperature variations. (Seinfeld et al., 2006) The small-scale climates within the planetary boundary layer have vertical scale of the order of 10 m^3, horizontal scale up to 10 ^{4}, the time scale of about 10^5 seconds during daytime. (Barry et al., 2003)

The boundary layer conditions differ from one location to another and across time in a given location. Climatic conditions in the boundary layer are characterized by the alterations in the urban surface. Compared to the surrounding rural landscape the urban area has a rougher, warmer and drier surface. (Whitford et al., 2004) Tall buildings and non-flexible objects make urban areas roughest in the aerodynamic boundaries. The aerodynamic roughness of a given terrain is described as roughness length (Z_0) or the height at which the wind speed falls to zero based on extrapolation of the neutral wind profile. (Monteith, 1975) Typical roughness lengths (m) corresponding to the surface characteristics are as shown in Table: 1.

Table: 1 Typical roughness lengths for a given surface

Surface Characteristics	Roughness lengths
Groups of high buildings	1-10 m
Suburbs	0.5 m
Farmland	0.05-0.1 m

Source: Troena and Peterson (1989) in Barry, 2003

Roughness length reduces wind velocity in urban spaces due to frictional effects. (Simpson, 1994) This localized slowing down of the air flow causes *" Pile up"* or converge over the urban canopy. (Oke, 1987) In high-density residential areas where the roughness lengths are higher the wind speed is slowed down and the direction of the wind may also be altered. While in rural areas or unimproved farmland the roughness lengths are relatively lower thereby not causing any significant obstruction to the wind flow and direction. The roughness lengths differ from one city to another depending on the surface structure and are important in temperature regulation of the city. (Barry 2003; Oke, 1978)

Winds set up the local pressures. For example airflow through topography barriers leads to gusts and winds. The time and lengths of these phenomenon cause short lived, small-scale turbulence in the boundary layer climate. (Oke, 1978; Barry et .al, 2003) The two types of turbulence in urban boundary layers are:

Laminar and Turbulent Urban Boundary Layers

Figure 4 depicts the laminar and turbulent boundary layer profiles.

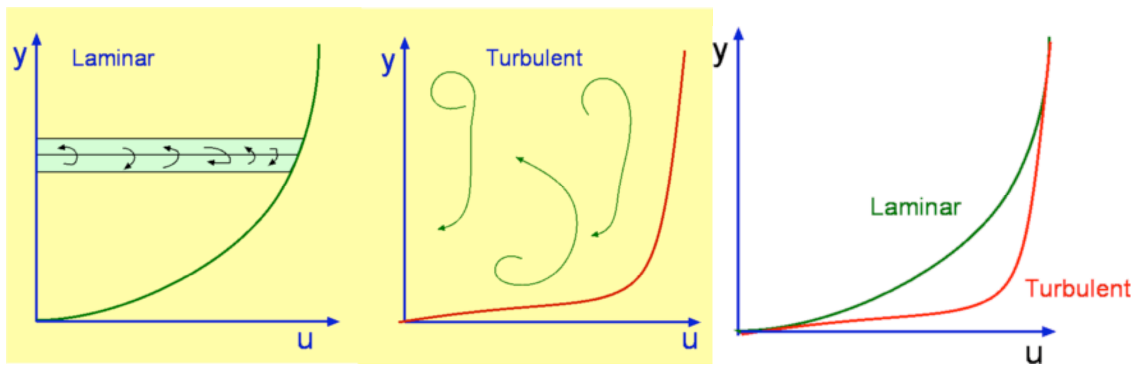

Figure 4: Typical velocity profiles for laminar and turbulent urban boundary layers
Source
http ://wwwmdp.eng.cam.ac.uk/library/enginfo/aerothermal_dvd_only/aero/fprops/introvisc/ltprofile.gif

In laminar urban boundary layers the streamlines are parallel to the surface. The flow of the momentum across the boundary is affected by the momentum exchange between individual molecules. Since the thickness of the laminar boundary layer cannot be increased indefinitely the flow becomes unstable and chaotic breaking the pattern into a swirl motion called turbulent boundary layer. Monteith states that, a second laminar layer of a restricted depth may form within the turbulent layer. In both laminar and turbulent layers, velocity increases with distance from the surface in a non-linear pattern as seen in Figure: 4. (Monteith, 1975; and Oke, 1995)

The energy exchanges and the creation of warm air inside the canyon and the boundary layer helps in the understanding of the urban heat island phenomenon. Before we discuss the Urban Heat Island let us look at the important aspects that help regulate temperature in the urban microclimates.

1.3 Factors affecting ambient temperatures

Urban morphology or characteristics is the distribution of different functions in an urban area that serves as a link between the human activities and natural processes. (Sandberg, 2003) Creation of cities requires modifications in the natural biophysical landscape with increasing amounts of land covered with buildings and structures that replace greens areas. (Cardelino, 1990) Heat capacity, a measure of the quantity of heat energy absorbed (or released) per unit volume of a material in response to a rise (or fall) in temperature of one degree, governs the ability of surface material to store thermal energy. (Oke, 1978) Urbanization alters the heat absorption, retention, thermal conductivity, reflectivity and emmisivity of built surfaces. For example the high density and the higher roughness lengths of the built structures enhances the ability of these surfaces to absorb incoming solar energy and trap outgoing long wave radiation. Surface reflectivity or the *albedo* explains the ability of the surface to reflect away the incoming solar radiation. For example dark surface colors and rough surfaces such as asphalt and bricks are efficient absorbers and poor reflectors of solar energy. (Seinfeld, 2006)

Evaporating faction is the proportion of surface that is available in urban conditions for evapo-transpiring. (Gill, 2007) Vegetation has lower heat capacities than cement and asphalt. Absence of large water bodies, vegetative areas and rapid drainage of surface water by runoff often leads to reduced evaporation. (Oke, 2003; Barry et al., 2003) Low vegetative cover in the built environment further contributes to urban heat. (Gill, 2007) Urban environments absorb and store large quantities of heat energy during the day, which is released gradually after a time lag in the late afternoons and evenings. This delay combined with a missing cooling process due to the lack of evaporating faction affects energy balance in urban environments. (Gill, 2007) Therefore, urban areas tend to remain warmer than their adjacent rural areas. Warm air retains higher percentage of moisture. This difference in relative humidity is clearly observable between urban and rural areas and moisture retention may be as much as 30% higher in the urban areas in the night as compared to rural areas. (Oke, 1995)

Wind profile is area where the speed is over a certain height above the surface of the Earth. (Monteith, 1975) Wind is defined in terms of a vector of its direction and the speed. Wind speed is a measure of air exchange and it describes the speed of the wind stream simultaneously demonstrating that the atmosphere pulls or pushes away air masses. (Seinfeld, 2006) The Table: 2 show the factors affecting wind speeds. There are two components to wind speeds vertical and horizontal. Hot air in urban areas rises up and this makes way for the cooler air from the rural surroundings. This is the vertical movement of the air. There are several aspects to the horizontal range.

Table: 2 Factors affecting wind speeds

Horizontal Range		Vertical range
Size and spatial factors	Meteorological factors	Spatial factor
Modifications of natural surfaces	Wind speeds-increased wind speeds weaken UHI intensity.	Urban canopy layer –heat is transferred from surface to the air above by convection
Built environments – roughness lengths	Clouds	
Anthropogenic heat emissions	Evapo-transpiration	

The most crucial factor amongst all is roughness lengths particularly in urban settings. Within the built up areas, an average of 20 to 30 % decrease in the wind speed at near ground may be observed. (Barry, 2003) The immediate vicinity of individual building structures and in the street area, there will be high velocity streams and eddies in the dry and dusty urban canyons leading urban airflow of 5m/s which is considered to be disturbance and 20m/s as dangerous to it inhabitants. (Santer, 1996)

A study conducted in London states that the surface wind speeds depend on upwind rural wind speed, season and the time of the day. The study also reports that when urban heat islands are well developed the wind speeds over urban areas could actually be higher than the rural surroundings. (Chandler, 1965) This is because the urban excess temperature creates a convergent “sea breeze “ circulation cell, with airflow near the surface directed into the warm city. (Barry, 2003) The cell superimposes any existing mean flow. (Bornstein et al., 1976) Chandler in 1965 also reports that nighttime urban wind speed was greater than the rural surroundings if regional winds were less than 5m/s. Similar observations have been reported from Ashaikawa in Japan. (Okita, 1965)

Wind speeds are directly proportional to the height above the ground level. The Figure: 5 shows the variances in wind profiles from city center to the periphery.

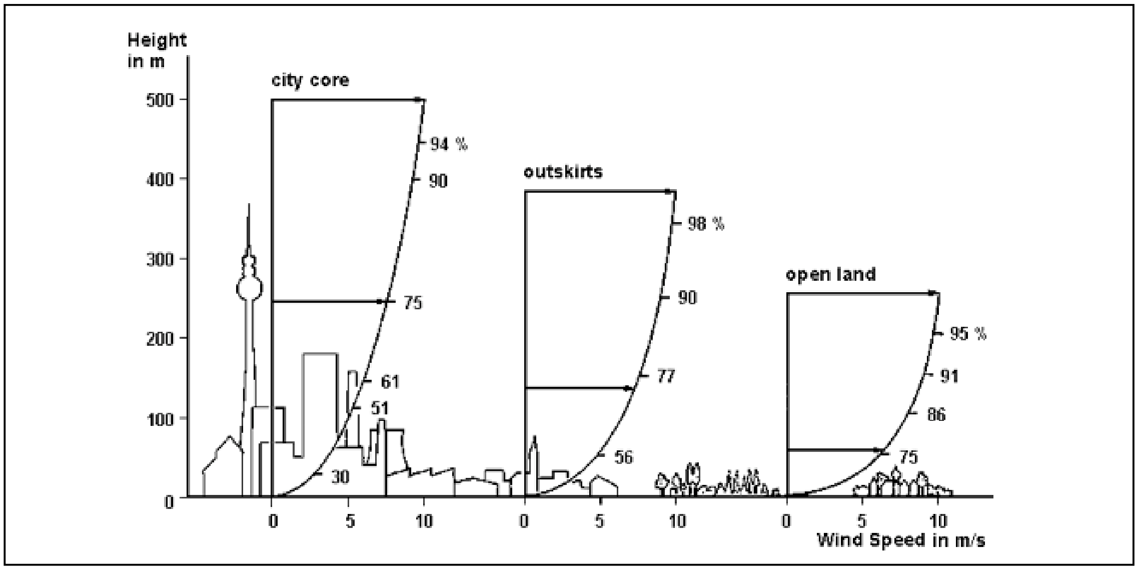

Figure: 5 The decisive determinant of the vertical profile of the wind speed is the respective terrain roughness
Source: http://www.stadtentwicklung.berlin.de/umwelt/umweltatlas/ed403_01.htm

The movement of air is complex in and around built environments. The surface roughness of structures produces turbulence. The built structures also determine where the air is channeled in the city, through the urban canyons and therefore there is a great difference in ground level velocity and the direction of the air in cities. (Sandberg, 2003) The built structures also influence the development of vortices; lees eddies and reverse flow of air (Seinfled et al., 2006; Barry et al., 2003).

Sheltering effect in the city weakens city winds speeds on an average of 5% as compared its surrounding areas or suburbs. (Barry et al., 2003) This effect varies seasonally as well as diurnally. The differences in urban and rural wind speeds are more pronounced during the winter seasons. (Oke, 1980) Thus the role of urban morphology is vital when discussing temperature variances particularly in city centres as they modulate wind speeds. Thus, morphology of urban land, lack of evaporative patches, utilization of excess energy generating waste heat, emissions and reduced wind speeds are primarily responsible amongst other causes for the rise in the ambient temperature in cities and drive the island effect.

1.4 The Urban Heat Island effect

Urban heat island (UHI) is an urban area that is considerably warmer than its rural surroundings. (Oke, 1987;Voogt, 2006) This temperature variation is usually larger in the night than during the day and more pronounced in winter than in summer. It is most exaggerated when the winds in the urban area are weak. (Oke, 1978) Urban heat island effect aggravates proportional to the size and growth of the city.

There are three types of urban heat islands (Barry et al., 2003; Voogt, 2006; Oke, 1987)

1. Canopy Layer Heat Island (CLHI): The heat island intensity increases with time from sunset to sunset and to predawn. During the day, the CLHI intensity is weak and there is a lag in the warming due to storage of heat by built surfaces that is released after a time lag.
2. Boundary Layer Heat Island (BLHI) is both during the day as well as during the night and is of small magnitude compared to CLHI and SHI.
3. Surface Heat Island (SHI) is strongly during the day and also is strong in the night. In the day this is evident due to the incoming solar radiation affects the surface in urban areas.

Canopy Layer Heat Island and Boundary Layer Heat Island refer to warming of the urban atmosphere and Surface Heat Island refers to the relative warmth of urban surfaces. Boundary layer heat island forms a dome of warmer air extending downwind of the city. The flow of the wind often changes the *dome* to a *plume* shape. (Voogt, 2006)

Figure: 6 show a city's heat island profile. It demonstrates how urban temperatures are typically lower at the urban-rural border zones than in dense downtown areas. Parks, open lands, and water bodies create comparatively cooler areas also seen in the graph.

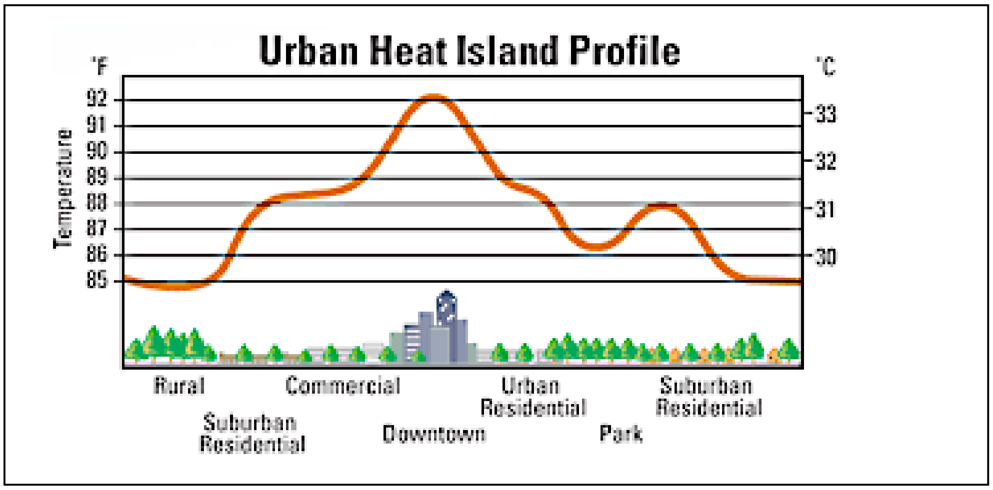

Figure 6: Profile of Urban Heat Island
Source: http://eetd.lbl.gov/HeatIsland/HighTemps/ Consulted on 26th Feb 2008

The most direct and detrimental human impact from urban heat island effect is heat stress. (Kovats et al., 2000) Increased mortality has been associated with extreme temperature events. Over 35,000 additional deaths, associated with the heat wave were reported in Europe in 2003. (Houghton , 2003[1]; Le Terte, 2002) The irony of the case lays in the fact the discomfort due to raise in temperatures supports the use air conditioners for cooling. The transient increase in the carbon dioxide emissions together with the increasing demand on energy supplies induces heat further increasing air temperature. Thus leading to a vicious circle from which we try to get out and at the same time contribute effectively to accelerate. Apart from the obvious effect on temperature, urban heat islands can produce secondary effects on local meteorology that includes altering of local wind patterns, development of clouds and fog, frequency of lightning strikes and the rise in the rates of precipitation.[2] The effect of urban heat islands on global warming are rather unclear. However, IPCC (AR4), 2007 indicates that there is negligible contribution of urban heat islands to the global rise in temperature.

[1] Houghton .J., Global Warming: The complete Briefing, Third Edition, Cambridge University Press, 2003

Given the complexities of natural climate systems as Dr Vicky Pope, Head of Climate Change for Government, Met Office Hadley Centre, UK puts it, scientists find it difficult to explain when and how these changes would occur or how severe the impacts would be Therefore climate modeling may be used to carefully design options for future adaptations.

1.5 Modeling for climate change

Climate models simulate the climate variations at spatial and temporal levels and help to understand the physical, chemical and biological processes that drive and alter climate. (Small, 2005) Models make future estimation possible by analyzing past and/or current climatic data. Mathematical equations are fixed with base line or base climates. (Arnfield, 1998) These are then used as reference indicators to calculate future variations and plot trends that may evolve in a given scenario. (Terjung, 1974) Due to inherent shortcomings of computations and the diverse scope of natural phenomena, these models are not predictive tools. (However they do provide opportunities to depict estimated changes. (Tso et al, 1989) Given these uncertainties researchers favour the development of better prediction models and the use of multiple models to better understand climate change. Figure: 7 show the increasing use of modeling in climate change studies over time. We are currently in 2000 –2010-time scenario for climate model development.

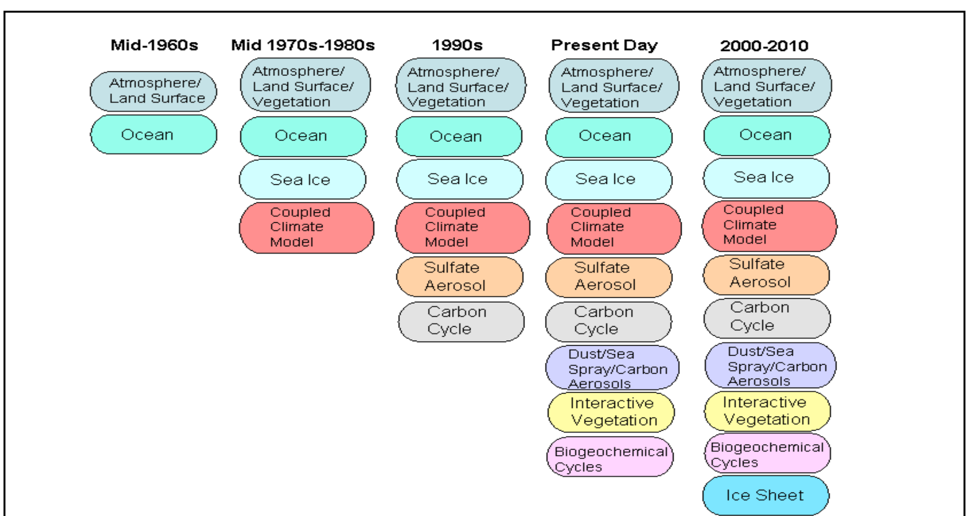

Figure 7: Timeline of climate model development
Source : www.windows.ucar.edu/teacher_resources/agu_fall2007/Killeen.ppt

Climate change models are classified into four main categories in the increasing order of complexity based the particular processes they simulate in spatial and temporal resolutions (MET office, 2008) and these are:

1) Energy Balance Models (EBMs)
2) One-dimensional Radiative-Convective Models (RCMs)
3) Two-dimensional Statistical-Dynamical Models (SDMs)
4) Three-dimensional General Circulation Models (GCMs)

The choice of the model is based on the nature of the study and the analysis required. The cost of computation will decide the model. The confidence in using these climate models depends largely on the understanding of the method in which the model simulates the processes in climate (Voogt, 2003; Oke, 1997). One criticism for modeling is that models often simplify the processes far more than the complex real life situations. Careful interpretation of model data and prediction is therefore essential.

Although, model functionality can be tested through simulations of shorter time scale processes, these may not reflect long-range accuracy. (Uncertainty can be resolved by repetitive experiments or by sensitivity studies where key assumptions are varied to study the role-played by a particular factor in the climatic response. (MET, Office 2008) Validation of climate models (testing against observed data) provides an opportunity to objectively test model performance. (MET, Office 2008)

The study and modeling for urban heat island effects through temperature and wind speed analysis have assisted in improved understanding of regional climatic conditions. (Roth et al., 1989) One such study (SCORCHIO project) currently underway in the city of Greater Manchester, UK. Sustainable Cities: Options for Responding to Climate Change Impacts and Outcomes (SCORCHIO) aims to develop tools with new forecasts to aid city planners, designers, engineers to improve adaptation to climate changes specifically in urban areas (http://gow.epsrc.ac.uk/ViewGrant.aspx?GrantRef=EP/E017649/1).

The current thesis is a part of the SCORCHIO project. To keep up with the aims of the overall project the scope of the thesis is to analyze the effects of wind speeds and roughness lengths on urban surface temperatures in Greater Manchester, UK. A sensitivity analysis of the Tso et al., 1990, 1991 energy balance model was conducted by model runs with varying wind speeds and roughness lengths. The modeled data were verified with the observed data obtained from the Meteorological office, UK.

1.6 Study Site

Greater Manchester, United Kingdom

Greater Manchester (See Figure: 8) is situated on the north west of the United Kingdom it is amongst the world's few cities that were born after the industrial revolution. The city is spread over approximately 1300 square kms along the river basin and the Pennine hills. It is 10 to 540 meters above the sea level. Over the past decades the city has experienced significant changes in its landscape and biophysical features due to urban development and large regeneration projects. (Gill, 2006)

Figure 8: Study Site, Manchester, UK
Source: www.bl.uk/images/uk-map.gif and www.chinalink.org.uk/img/Manchester%20Skyline.GIF

Greater Manchester is vulnerable to high temperatures but has not been appropriately designed for warmer temperatures. Any further expansion in the city may spell discomfort and stress to the population. The results from a previous study done by Gill (2006) found that the central business district preserved the stock up heat from the previous day until sunrise the following morning. This explains why these locales are warmer by night as compared to the neighboring suburbs and surrounding rural areas.

Intensity of Urban Heat Island effect in Greater Manchester

The study conducted by Mark Wilson to assess the urban heat island effect in Greater Manchester in the summer of 2003 identified that the peak hours of intensity are affected by the wind speeds and/or by the cloud cover in Greater Manchester. Another problem specific to the city was inconsistent data for most part of the day.

The Figure: 9 show the average heat island intensity for the sample summer months of 2003 chosen by Wilson for his study on heat intensity in Greater Manchester.

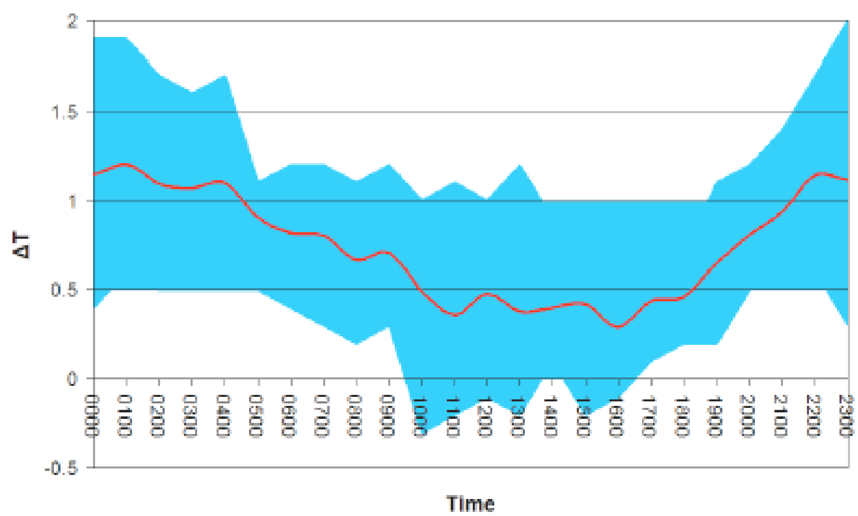

Figure 9: Average Heat Island Intensity for Greater Manchester in June 2003. The red line indicates the average values and the shaded areas represent the range of 70% of the observation. (Wilson, 2003)

It is important to consider two morphology variables while studying the urban heat island effect in the city of Greater Manchester.

1. Canyon geometry
2. Orientation of the canyon with respect to wind direction.

The relationship between the urban and rural wind velocities is the expression of maximum heat island intensity in terms of sky view factor. (Oke 1981) The effect of sky view factor on heat island intensity in Urban Manchester showed that when the wind velocity factor increases the maximum heat island intensity decreases linearly. The difference in temperature between Hulme and Ringway was mainly because of the higher admittance of the urban materials in warm dry conditions leading to a time lag in urban cooling. This relationship allows the maximum heat island intensity to be calculated only when wind velocities are known for an urban and rural site. (Wilson, 2003)

Chapter 2
Aims and Objectives

The study aims to evaluate the impact of wind speeds on urban surface temperatures and hence on the urban heat island effect during the summer months of June, July and August 2007 in Greater Manchester, UK. The current thesis analyzes the sensitivity of the Tso (1990; 1991) simple energy balance model to varying wind speeds and roughness lengths. The modeled data is verified by comparing it to observed Meteorological Office data, UK.

The main objectives of the study are:

Primary

- To study the impact of wind speeds on urban surface temperatures and hence on the urban heat island effect in Greater Manchester.

Secondary:

- To analyze the sensitivity of the Tso et al., 1990; 1991 energy balance model to varying wind speeds and roughness lengths
- To verify the Tso et al., 1990; 1991 urban energy balance model for its ability to estimate urban surface temperatures accurately.

Chapter 3
Material and Methods

In order to conduct sensitivity tests on the Tso urban energy balance model. Tests were run on a model-by-model basis with varying wind speeds and roughness lengths for urban and rural environments. The difference in surface temperature in the city and its surrounding rural areas was recorded to understand the urban heat island impact. To check for model accuracy the real air temperature data obtained from the Meteorological office dataset for Hulme (as an urban environment) and Woodford (as rural environment) were used.

The current chapter introduces the sensitivity test for the study followed by the description of the Tso urban energy balance model. The chapter is based on the notes from Whitford, 2003; Gill, 2006; Tso et al., 1990,9991; and Wilby, 2003. The subsections present input parameters used for the model runs.

Sensitivity Test

Sensitivity tests are undertaken to understand model efficiency. Different parameters were used for marking sensitivity to surface temperature output. Wind speed input parameter was altered for each run (by a suitable value for urban and for rural environment) keeping all the other parameters constant for a given condition. This process was repeated for the roughness length parameter (for both urban and rural environment) to obtain surface temperature values

3.1 The urban energy balance model (Gill, 2006; Whitford et al., 2001; Wilby, 2003)

The Tso energy balance model was developed by Tso et al., in 1990-1991 for the study in Merseyside and later used by Gill, in her study in Greater Manchester, UK in 2006. The Tso model expresses the surface energy balance of an area in terms of its surface temperature. The output results of the model are in surface and soil temperatures as a function of time. The model is based on the following core assumptions: (Gill, 2006)

1. All the meteorological and soil parameters remain constant horizontally.
2. The transfer of heat and water vapour is near neutral.
3. On the boundary layer the heat fluxes and water vapour are constant.
4. On surface boundary layer wind speed, temperature and specific humidity are constant.
5. The urban canopy has a fixed roughness length.
6. Human induced heat sources are not accounted for.

Framework of the Tso Model:

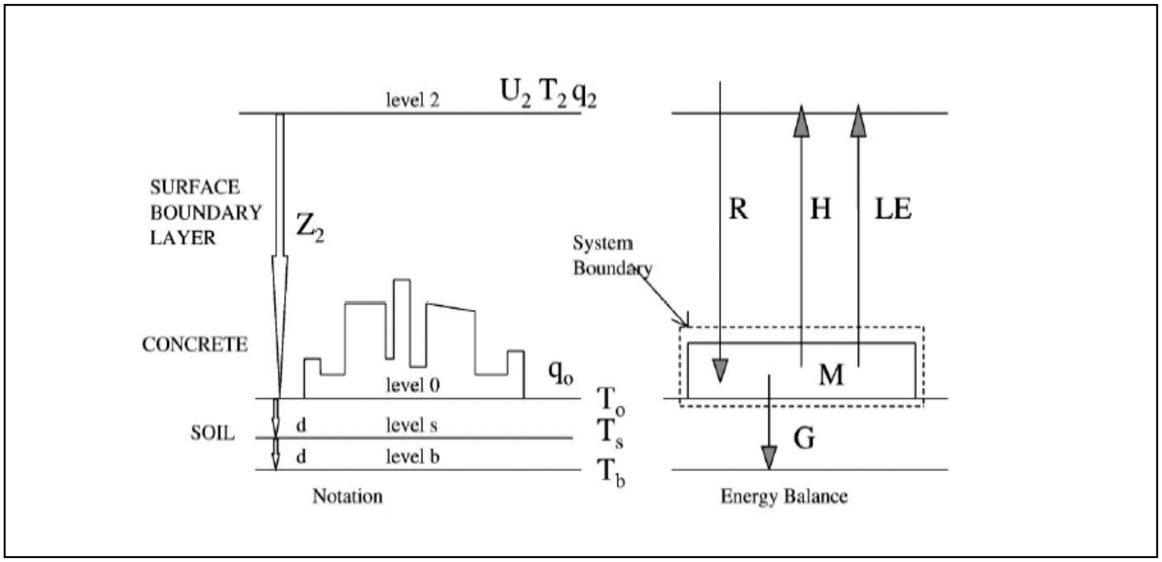

Figure 10 : the Framework of the Tso Model

Source: Framework of the urban energy balance model (Tso et al., 1990, 1991)

The Figure 10 shows the framework of the model.

Equation of the Tso model Tso et al. (1990,1991):

The model is based on the simple direct urban energy balance equation as seen in Figure: 11

Energy Balance Equation

$$R=H+LE+G+M$$

Where

R = net radiation flux to the earths surface
H = sensible heat flux due to convection
LE = latent heat flux due to evaporation
G = conductive heat flux into soil
M = heat flux to storage in the built environment

Figure 11: Model equation

The model accounts for urban environments by incorporating building mass and heat storage effects. Whitford et al., (2001) developed a computer program of the model in Mathematica that analyses the relation between the parameters in a symbolic form seen in Figure: 12. The parameters are assigned respective numeric values, starting with those that are similar to each condition followed by those that differ for urban and rural environments. The model then linearises specific parameters around reference temperatures to model an output data in the form of surface temperatures.

Model structure in Mathematica

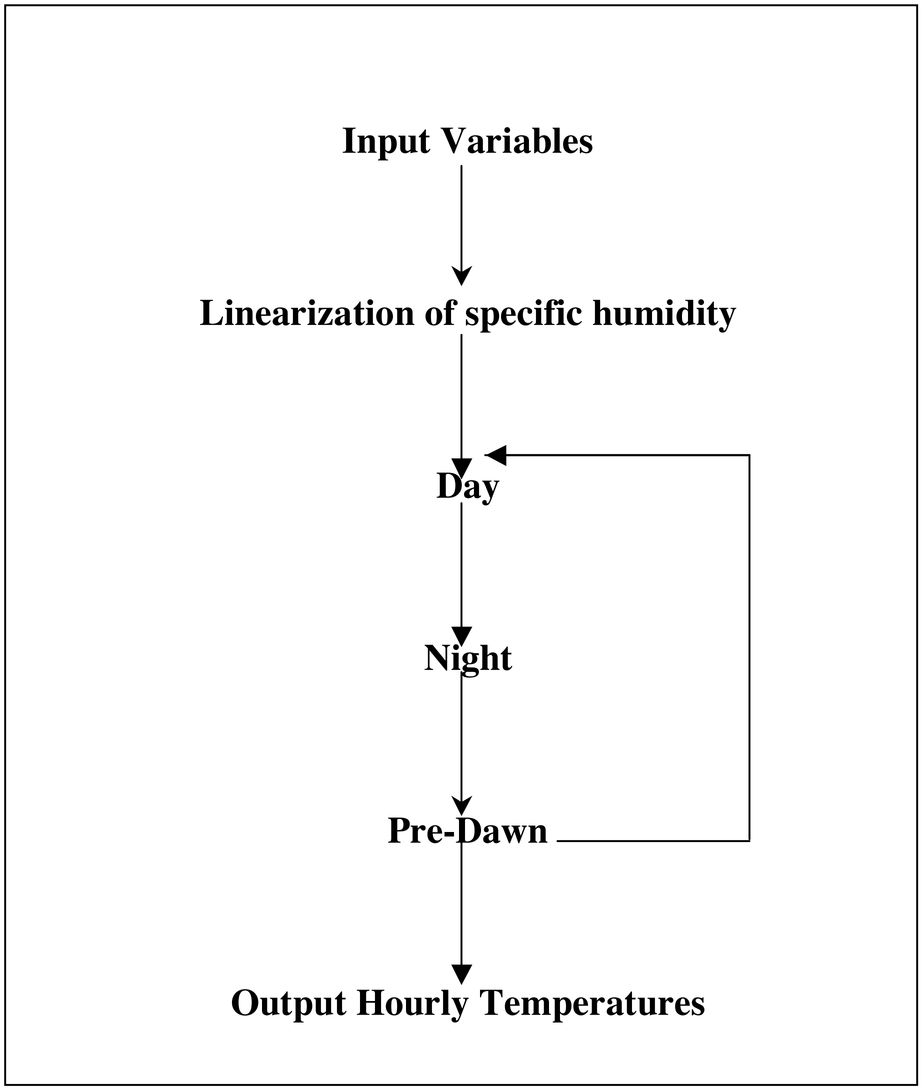

Figure 12: Modified model structure of the Tso urban energy balance model.

The model divides the day into three periods: sunny, night (i.e. from sunset time to midnight) and pre-dawn (i.e. from midnight to sunrise). A repetitive process of changing the parameters for wind and roughness is then followed for each urban and rural condition. Figure: 13 shows the data of hourly output of temperature results of time (24

hours) when plotted on a graph after transferring the output values in Microsoft Excel®
for improved quality of graphs.

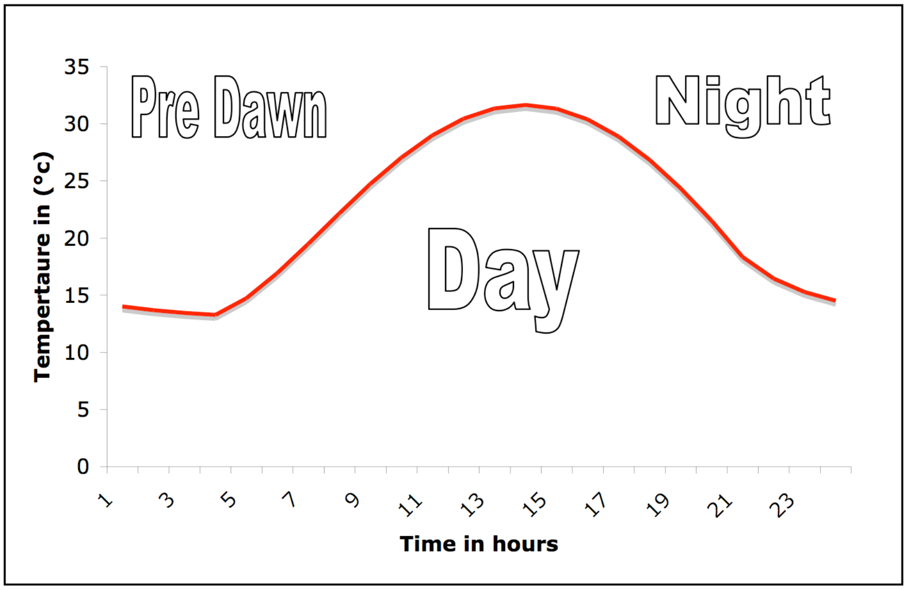

Figure 13: The Tso urban energy balance model hourly outputs of temperature in a day

3.2 Parameters that varied for model runs

The model runs were conducted for the different wind speeds and roughness values. The parameters with numerical values remain constant throughout the model runs performed. The other parameters vary. The Table: 3 shows the exact parameters that were varied for model runs in our study

Table: 3 Input data parameter that varied for the model runs.

Parameters	Source	For urban environment	For rural environment
U2	MET Office, UK, 2008	3.67m/s, 7.34m/s, 11.01m/s	3.67m/s, 7.34m/s, 11.01m/s
Mc	Gill, 2006	352	1.28
Zo	Oke, 1978	2,4,6 and 10	0.1,0.2,0.3
Ef	Oke, 1978	0.31	0.91

3.3 Input parameters for model runs

Relevant parameters for wind speeds and roughness lengths for Greater Manchester were downloaded from the MET office, Government of UK website. These data were long- term monthly averages from 1971 to 2000 for winds recorded 10 m from Greater Manchester airport. The data were in *knots* values and were converted to m/s values for input into the model. The data for the summer study months of June, July and August were extracted. The Table: 4 shows the average wind speeds for these three months.

Table: 4 Average wind speeds for summer months

Months	Wind speeds from Meteorological office website in Knots	Wind speeds in m/s	Average wind speeds
June	7.4	3.81 m/s	3.67m/s
July	7	3.60 m/s	
August	7	3.60 m/s	

An average of the wind speeds of these three months (3.67 m/s) was used to evaluate the effect on the surface temperature in both urban and rural environment. To analyze the difference in the surface temperature for varying wind speeds, twice (2x 3.67= 7.34 m/s) and thrice (3x 3.67 = 11.01 m/s) the monthly average was used.

Urban Environment- Input parameters

1. Effects of varying wind speeds on surface temperature:

To analyze the effect of varying wind speeds on surface temperatures in the urban two times the average of the three-summer months (2x 3.67) and then three times the average of the three summer months (3x 3.67) wind speeds were used. This was done keeping the roughness length constant at 2 m, evaporation factor constant at 0.31 and building mass for high residential areas constant at 352.62 mc relevant to urban areas. The Table: 5 summarize input parameters.

Table: 5 Model run parameters for effects of varying wind speeds on surface temperatures in urban environment.

Model runs	Wind speed	Evaporation Factor	Building mass for high density residential area	Roughness Lengths
Run 1	3.67m/s	0.31	352.62 mc	2 m
Run 2	2x 3.67= 7.34 m/s	Constant	Constant	Constant
Run 3	3x 3.67 = 11.01 m/s	Constant	Constant	Constant

2. Effects of varying roughness lengths on surface temperatures:

Roughness increases turbulence in airflow in urban environment that helps dispersion of heat from the city centre. Model runs were made with varying roughness lengths to analyze its influence on surface temperature in urban environments. This was done by keeping the wind speed constant at 3.67 m/s, evaporation factor constant at 0.31 and building mass for high residential areas at 352.62 mc. The Table: 6 summarize input parameters used.

Table: 6 Input parameters for effects of varying roughness lengths on surface temperatures in urban environment.

Model runs	Roughness Lengths	Evaporation Factor	Building mass for high density residential area	Wind Speed
Run 1	2 m	0.31	352.62 mc	3.67 m/s
Run 2	4 m	Constant	Constant	Constant
Run 3	6 m	Constant	Constant	Constant
Run 4	10 m	Constant	Constant	Constant

Rural environment- Input parameters

1. Effects of varying wind speeds on surface temperature:

To analyze the effect of varying wind speeds on surface temperatures in the rural areas two times the average of the three-summer insulation months (2x 3.67) and three times the average of the three summer insulation months (3x 3.67) were used. This was done keeping the roughness length constant at 0.1 m, evaporation factor constant at 0.91 and building mass per unit of land for unimproved farmland constant at 1.28 mc relevant to rural environment. The Table: 7 summarize the input parameters used.

Table: 7 Model run parameters for effects of varying wind speeds on surface temperatures in rural environments.

Model runs	Wind Speeds	Evaporation Factor	Building mass per unit of land for unimproved farmland	Roughness Lengths
Run 1	3.67 m/s,	0.91	1.28 mc	0.1 m
Run 2	7.34 m/s	Constant	Constant	Constant
Run 3	11.01 m/s	Constant	Constant	Constant

2. Effects of varying roughness lengths on surface temperatures:

Model runs were made with varying roughness lengths to analyze the influence on surface temperature in rural environment. This was done by keeping the wind speed constant at 3.67 m/s, evaporation factor constant at 0.91 and building mass per unit of land for unimproved farmland at 1.28mc. The Table: 8 summarize the input parameters used.

Table: 8 Input parameters for effects of varying roughness lengths on surface temperatures in rural environment.

Model runs	Roughness Lengths	Wind Speed	Evaporation Factor	Building mass per unit of land for unimproved farmland
Run 1	0.1	3.67m/s	0.91	1.28
Run 2	0.2	Constant	Constant	Constant
Run 3	0.3	Constant	Constant	Constant

3.4 Air and surface temperature difference in Greater Manchester

The Tso model run output data gave values for ***surface temperatures***. These were compared with observed data obtained Meteorological office, UK. For comparison, unpublished 2007 monthly data for the three summer months (June, July August) was extracted. The days with maximum air temperature and wind speeds were identified and the 24hr values for these days averaged. The values of observed wind speed and air temperatures thus obtained from Meteorological office, UK dataset were compared modeled data. This allowed verification of the model for accuracy.

However, the observed temperature data used as reference for comparison was available for ***air temperatures.*** This discrepancy was resolved by taking into account the differences in air and surface temperature for Greater Manchester and are summarized in Table: 9. The results from the tests of the model runs are presented in chapter 4.

Table: 9 Data from the transects explaining the difference between surface and air temperatures in Greater Manchester.

Condition	Surface Temperature	Air Temperature
Improved farmland	13.58 ° C	12.26 ° C
High density residential area	14.22 ° C	13.10 ° C

These were taken in October 2007 on a clear day hence the lower temperatures (SCORCHIO project, 2008).

Chapter 4
Results

This chapter presents the results in four sub- sections. The first sub-section presents output results from the Tso model for urban and rural surface temperatures. Second section describes the differences in urban and rural temperatures at varying wind speeds. Section three presents the modeled data for urban and rural environments for Greater Manchester. Finally, the comparison between modeled data and observed data is presented in sub-section four.

4.1 Tso model output data

4.1.1 Urban Environment

Output results for model runs with varying wind speeds for urban environment

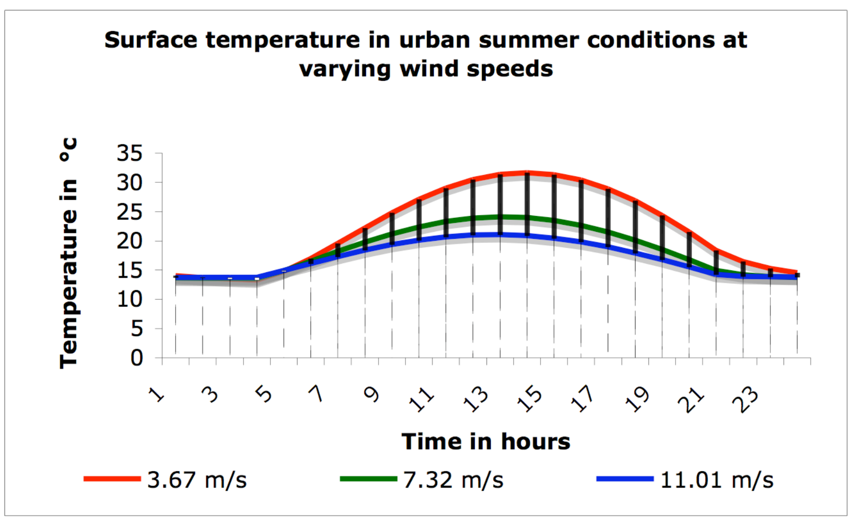

Figure 14: Surface temperature at varying wind speeds for urban environment.

The Figure: 14 show the output of surface temperatures in the three summer months for twenty-four hour period. The out put result show that as the wind speed increases the temperature in the city decreases as seen in Table: 10. The dark blue line shows the result of average wind speed parameter of 3.67m/s the surface temperature is 31.62 ° C at 14.00 hours in the urban condition.

Table: 10 Surface temperature readings at varying wind speeds for urban environment.

Model Runs	Wind speed	Observed surface temperature	Time of Observation	Evaporation Factor	Building mass for high density residential area	Roughness Lengths
Run 1	3.67m/s	31.62°C	14.00hrs	0.31	352.62 mc	2 m
Run 2	7.34 m/s	24.07°C	13.30hrs	Constant	Constant	Constant
Run 3	11.01 m/s	21.05°C	13.30hrs	Constant	Constant	Constant

When testing for twice the average of the summer months wind speed (7.34 m/s) the surface temperature decreased to 24.07°C observed around 12.00 hours. When the wind speed was further increased to 11.01m/s the surface temperature dropped to 21.05°C at 12.00 hours.

Output results for model runs with varying roughness lengths for urban environment:

The Figure: 15 shows the surface temperatures at varying roughness lengths for urban environments

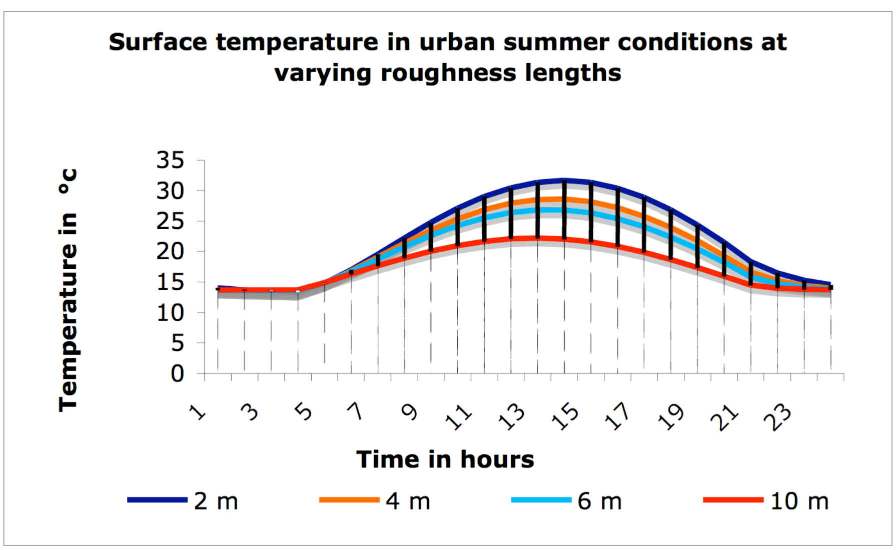

Figure: 15 Surface temperatures at varying roughness lengths for urban environment.

When the model runs were conducted for urban areas the roughness length was varied at 2m, 4m, 6m, and 10m and the corresponding observed surface temperatures were 31.62° C, 28.56°C, 26.77°C and 22.99°C respectively between 12.00-13.00 hrs as seen in the Table: 11.

Table: 11 Surface temperature readings at varying roughness lengths for urban environment.

Model Runs	Roughness Lengths	Observed Surface temperature	Time of Observation	Evaporation Factor	Building mass for high density residential area	Wind Speed
Run 1	2 m	31.62°C	12.00 noon	0.31	352.62 mc	3.67 m/s
Run 2	4 m	28.56°C	13.00 hrs	Constant	Constant	Constant
Run 3	6 m	26.77°C	12.00 noon	Constant	Constant	Constant
Run 4	10 m	21.99°C	12.00 noon	Constant	Constant	Constant

Similar the model runs were made to observe the changes in surface temperature with varying wind speeds and roughness lengths for rural environment and the results are as follows.

4.1.2 Rural environment

<u>Output results for model runs with varying wind speeds for rural environment:</u>

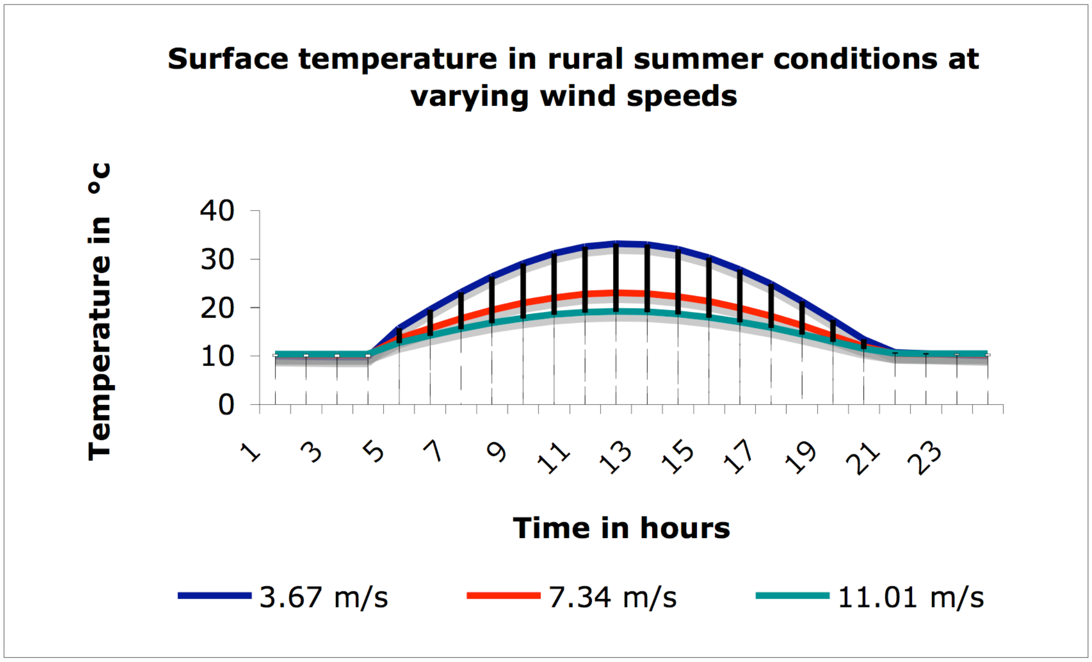

Figure 16: Surface temperature at varying wind speeds for rural environment.

The Figure: 16 shows the surface temperature observations for rural environment. When wind speeds were varied from 3.67 m/s, to 7.34 m/s and 11.01 m/s the observed temperature decreased from 33.09 ° C to 22.99°C and 19. 18°C respectively at 12.00 - 16.00hrs on a clear day as seen in Table: 12

Table: 12 Surface temperature readings at varying wind speeds for rural environment.

Model Runs	Wind Speeds	Observed surface temperature	Time of Observation	Evaporati on Factor	Building mass per unit of land for unimproved farmland	Roughne ss Lengths
Run 1	3.67 m/s,	33.09 ° C	12.00 noon	0.91	1.28 mc	0.1 m
Run 2	7.34 m/s	22.99 ° C	12.00 noon	Constant	Constant	Constant
Run 3	11.01 m/s	19.18 ° C	12.00 noon	Constant	Constant	Constant

Output results for model runs at varying roughness lengths for rural environments:

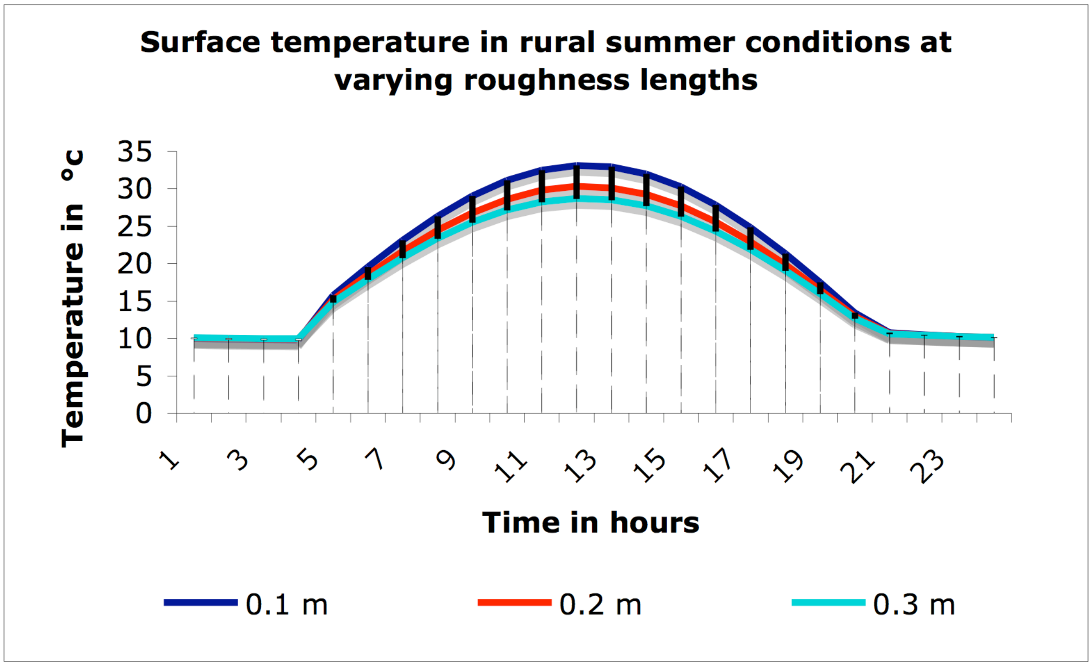

Figure 17: Surface temperature at varying roughness lengths for rural environments.

Increasing the roughness length from 0.1m to 0.3m the surface temperature decreased from 33.09°C to 28.68°C respectively in rural environment as seen in Table: 13.

Table: 13 Surface temperature readings at varying roughness lengths for rural environment

Model Runs	Roughness Lengths	Surface temperature	Time of Observation	Wind Speed	Evapora tion Factor	Building mass per unit of land for unimproved farmland
Run 1	0.1	33.09° C	12.00 noon	3.67m/s	0.91	1.28
Run 2	0.2	30.28°C	12.00 noon	Constant	Constant	Constant
Run 3	0.3	28.68°C	12.00 noon	Constant	Constant	Constant

4. 2 Urban- rural surface temperature differences at varying wind speeds

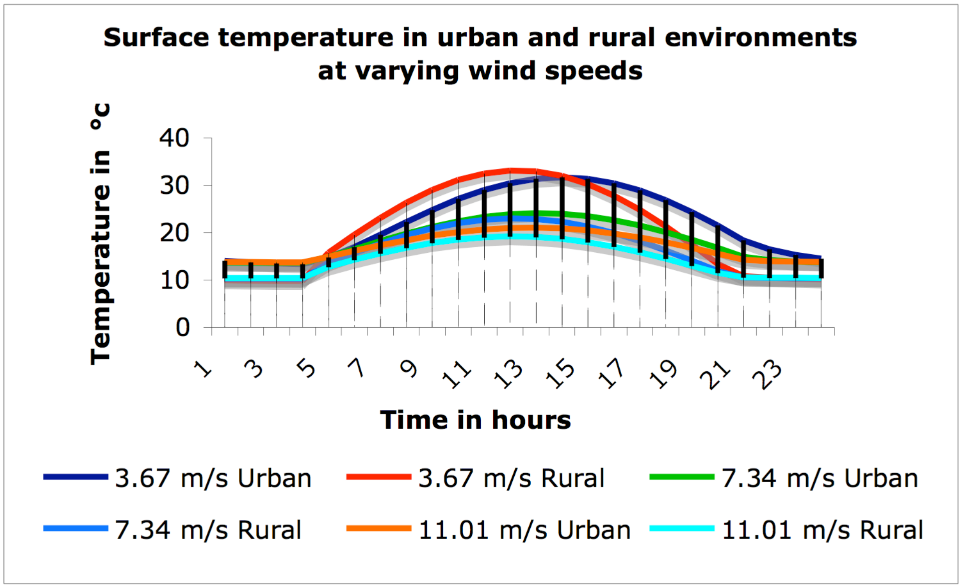

Figure 18: Observed difference in urban and rural surface temperatures at varying wind speeds

The Figure: 18 show the differences observed in urban and rural surface temperatures at varying wind speeds. During peak afternoons in urban environment (represented in dark blue line) the recorded surface temperature was 31.62°C between 14.00hrs and that in rural environment was 31.16°C at 14.00hrs. In early afternoon rural temperature was higher than urban temperature. However, the difference reversed in the later part of the day from 15.00 -23.00hrs. The urban surface temperature at 21.00hrs was 18.33°C and rural was 10.76°C, a substantial difference of 8°C. Thus the variance in surface temperature was more pronounced at night with urban areas far warmer than the rural. Table: 14 summarize the difference between urban and rural environment at 21.00hrs at varying wind speeds.

Table: 14 Observed differences in urban and rural surface temperatures at varying wind speeds

Hours (Time)	Varying Wind speeds	Urban condition	Rural Condition	Difference in surface temperatures
21.00	3.67 m/s	18.33 ° C	10.76 ° C	8 ° C
21.00	7.34 m/s	14.89 ° C	10.49 ° C	4 ° C
21.00	11.01 m/s	14.25 ° C	10.52 ° C	4 ° C

4. 3 Observed data for urban and rural environments in Greater Manchester.

4.3.1 Urban condition (Hulme)

Average wind speeds for the three summer months June, July and August 2007

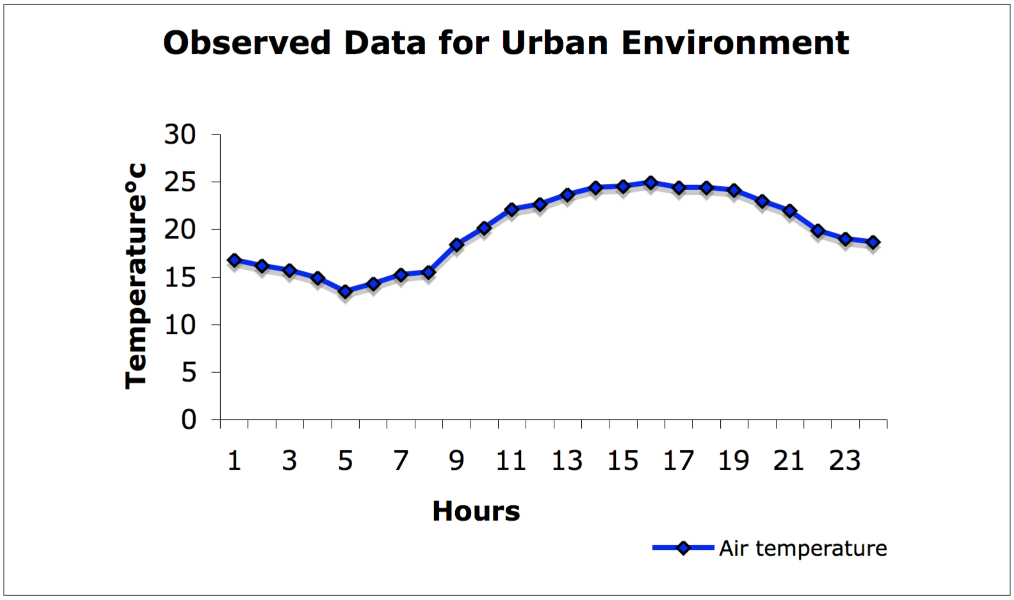

Figure 19: Average wind speeds for summer 2007 in urban environment

The Figure: 19 shows the average air and wind speeds observed over the 24 hr period observed on this day.

Table: 15 Maximum average air temperature and wind speeds in urban environment

Duration of study observation	Average wind speed 15.00- 17.00hrs	Average observed air temperature at 16.00hrs
June 11, 2007	7.33 m/s	24.93°C

The average air temperature was 24.9 °C while the average wind speed was 7.33 m/s on June 11, 2007 warmest day of the summer months in urban environment as shown in Table: 15.

4.3.2 Rural environment

Average air temperature over the 24 hrs period for 16.06.07 in rural environment

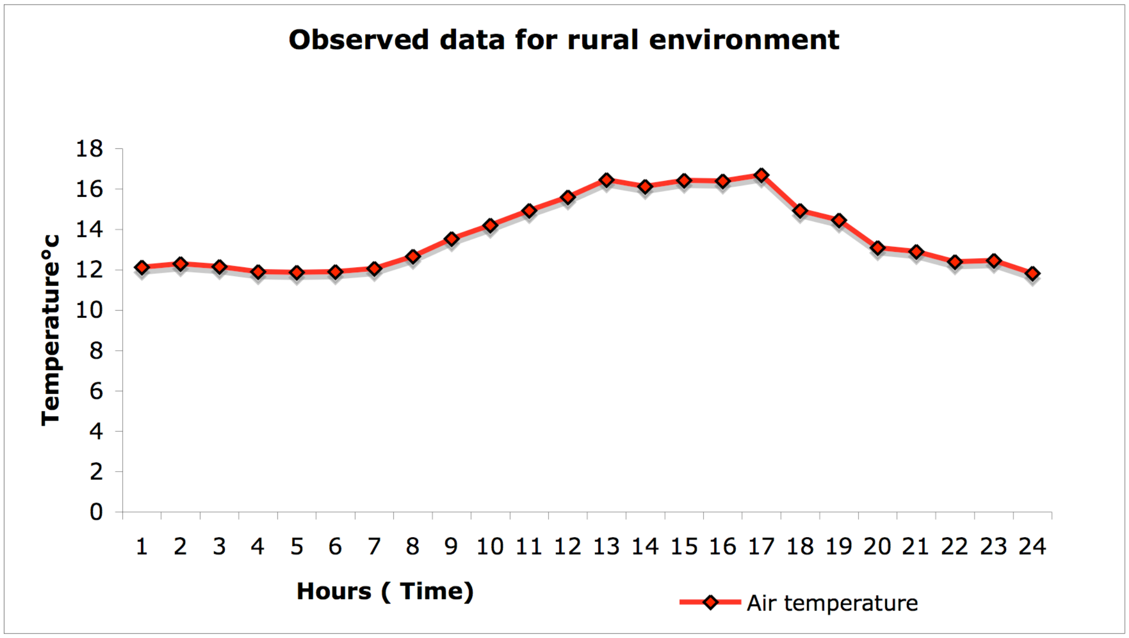

Figure 20: Average air temperature over the 24 hrs period for 16.06.07 in rural environment

The Figure: 20 shows the average air temperature observed over the 24 hr period observed on 16. 06. 2007 the warmest day.

Table: 16 Maximum observed average air temperature and wind speeds in rural environment

Duration of study observation	Average wind speed 18.00hrs	Average observed air temperature at 13.00hrs
June, July and August 2007	7.66 m/s	16.46°C

The average air temperature was 16.46°C while the average wind speed was 7.66 m/s on June 16, 2007 warmest day of the summer months in rural environment (Woodford) as shown in Table: 16.

4.4 Comparison between modeled data and observed data

4.4.1 Urban environment

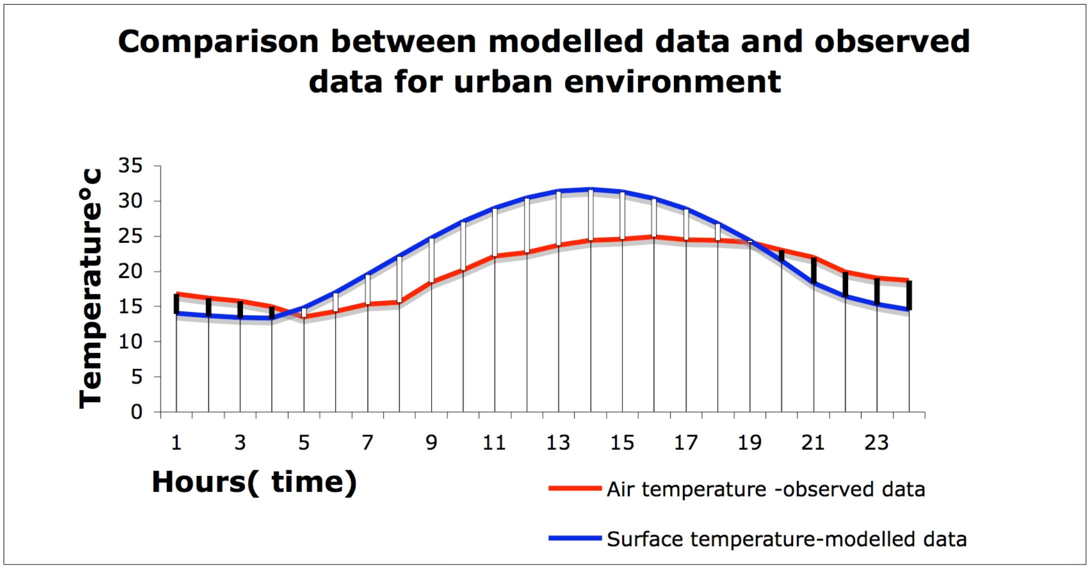

Figure 21:Tso model findings vs. real data for urban environment

The Figure: 21 show the comparison between the model run output results (surface temperature) and real data (air temperature) in urban environment.

Table: 17 Maximum temperature output by modeled data vs. observed data for urban environment

Parameter	Observed Max.Temperature	Hour (Time)
Surface temperature	31.62°C	14.00hrs
Air temperature	24.93°C	16.00hrs

The Table: 17 show the temperatures and the corresponding time when the peak temperatures were observed. The model run output gives the maximum surface temperature of 31.62°C observed at 14.00hrs while the maximum-recorded real data air temperature was 24.93°C in urban environment.

4.4.2 Rural environment (Woodford)

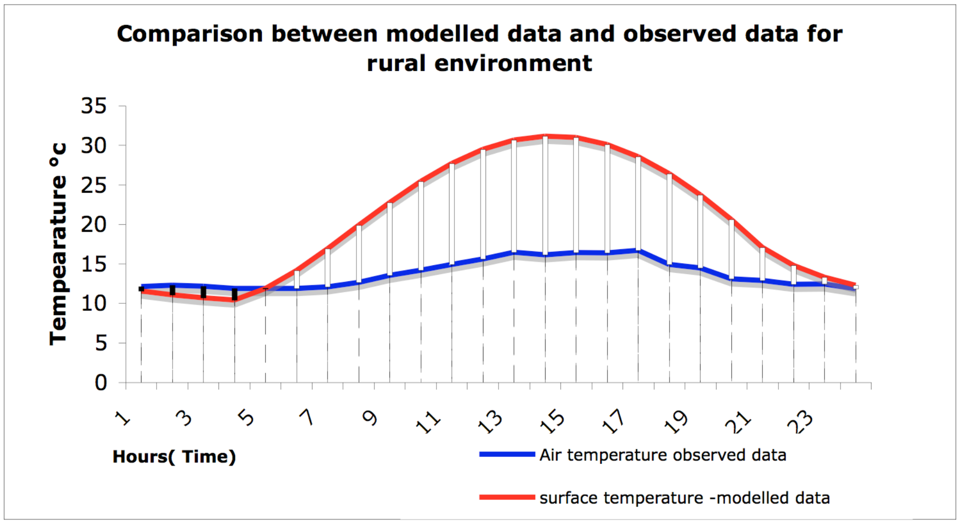

Figure: 22 Tso model findings vs. observed data for rural environment

The Figure: 22 show the comparison between the modeled data (surface temperature) and observed data (air temperature) in rural environment.

Table: 18 Maximum temperature output by Tso model vs. observed maximum temperature for rural environment

Parameter	Observed max. Temperature	Hour (Time)
Surface temperature	33.09 ° C	12.00hrs
Air temperature	16.46 ° C	13.00hrs

The Table: 18 show the temperatures and the corresponding time when the peak temperatures were observed. The maximum modeled surface temperature of 33. 09°C observed at 12.00 hrs while the maximum observed air temperature was 16.46 °C in rural environment.

Chapter 5 will the discuss the difference between air and surface temperature to further compare the modelled data with observed data from urban condition rural environment.

Chapter 5
Discussion

5.1 Effect of wind speed on surface temperatures

The pattern of surface temperatures in summer conditions at varying wind speeds observed in Greater Manchester in both model runs and observed data suggest that wind speeds affect surface temperatures in both urban and rural environments. The modeled data showed that the maximum surface temperature was 31.62 °C at wind speed of 3.67 m/s which dropped to 24.07°C and 21.05°C with accelerated wind speeds of 7.34 m/s and 11.05 m/s respectively at 13.00hrs in the day (See Table: 10 in Results). The observed data from Meteorological office supported these findings. Similar observation was made in the rural model run at varying wind speeds. With wind speed of 3.67 m/s the output surface temperature was 33.09 °C at 12.00 noon. At increasing wind speeds of 7.34 m/s and 11.01 m/s the surface temperature dropped to 22.99 °C and 19.18 °C both at 12.00 noon respectively (See Table: 12 in Results). The urban Meteorological Office data supported these findings.

Both modelled (surface temperature) and observed (air temperature) data demonstrate that reduced wind speed enhances rise in the temperature in both urban and rural environments. These temperature differences were significantly apparent in urban conditions. At increasing wind speeds the urban-rural variances were more pronounced.

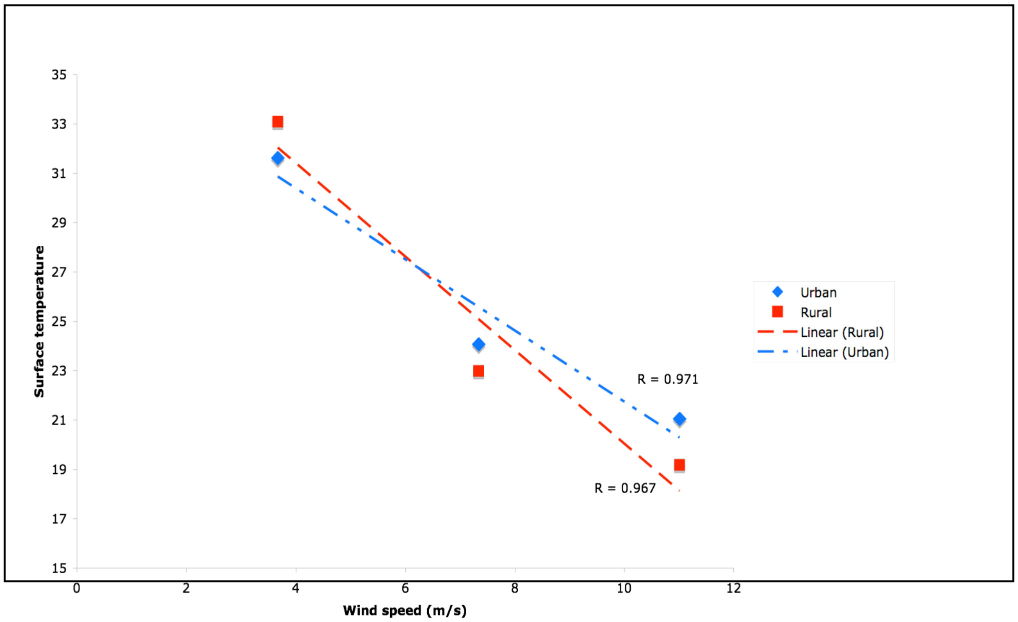

Figure: 23 Correlation between wind speeds and surface temperature in urban and rural environments

Figure: 23 show the correlation between wind speeds and temperature for modelled urban and rural environments. The coefficient of determination *R* for urban environment is 0.971 and *R* for rural environment is 0.967. The scatter plot shows how wind speeds affects temperature in both rural and urban areas similarly. However, increasing wind speeds rapidly decrease rural temperatures to a significantly low value. Therefore the difference in urban –rural temperatures is more pronounced as also seen in Figure 24. This means that the wind would affect urban heat islands in Greater Manchester.

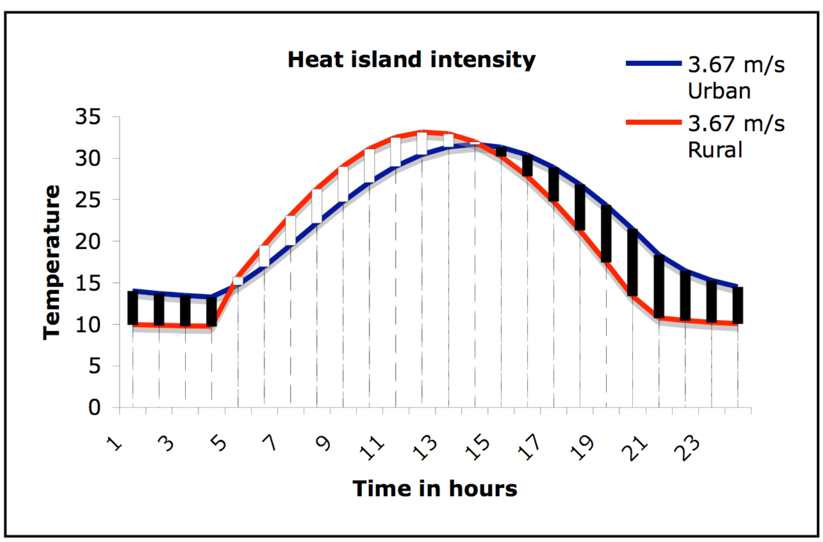

Figure 24: Heat Island Intensity

5.2 Effects of roughness lengths on surface temperature

Roughness lengths also affected surface temperatures. With roughness lengths of 2m, the modeled urban environment temperature was 31.62°C. At varying roughness lengths of 4m, 6m, and 10m the surface temperatures were 28.56°C, 26.77°C and 21.99°C respectively from 12.00hrs to 13.00hrs in the day (See Table: 11 in Results).

Similar observations were made in modeled temperatures for rural environments. The modeled surface temperature at roughness length of 0.1m was 33.09°C. As the roughness length increased from 0.2m to 0.3m the surface temperature dropped to 30.28°C and 28.28°C respectively (See Table: 13 in Results).

The results from the study confirm an inverse relation exists between both- wind speeds and surface temperatures as well as roughness lengths and surface temperatures, for both urban and rural environments. Let us then look at the nature of these variations.

5.3 Diurnal Temperature Variances

Urban environment: modeled data

The variances in the 24hrs period for the day with maximum temperature in urban environment in the summer insolation months at varying wind speeds are as follows.

Table: 19 Surface temperature and time of days with maximum temperatures in urban environment (Modelled data)

	Surface Temperature and time		Wind speeds
	Maximum temp/Time	Minimum temp /Time	
Day one	31.62ºC- 14.00hrs	13.43ºC- 3.00hrs	3.67 m/s
Day two	23.94ºC-14.00hrs	13.54ºC -3.00hrs	7.32 m/s
Day three	20 .87ºC-14.00hrs	13.73ºC-3.00hrs	11.01 m/s

The maximum temperature for urban-modelled data was at 14.00hrs with temperature of 31ºC when the wind speed was 3.67m/s for that particular day. The minimum temperature modeled was 13.43ºC at 03.00hrs. With varying wind speeds the same trend was observed. The maximum temperature for day two and day three was at 14.00hrs and the minimum temperature was modeled at 03.00hrs in the morning as seen in Table: 19.

Urban environment: Observed data (Hulme)

The variance in 24hrs period on the day with maximum air temperature in the observed data are shown in the Table: 20.

Table: 20 Air temperature and time of the day with maximum temperatures in urban environment (Observed data).

	Air Temperature and time		Wind speeds
	Maximum temp/Time	Minimum temp /Time	
Day one	24.93 º C- 16.00hrs	13.46 º C- 5.00hrs	7.33m/s/2.66m/s

Where the maximum air temperature was at 16.00hrs and the minimum air temperature at 05.00hrs. This maximum temperature of 24.93ºC is with the maximum wind speeds on that day. As per available literature the maximum temperature is recorded at midday when the maximum solar radiation is absorbed and maximum long wave radiation is emitted by the heated surface. After this the temperature drop in the evening due to minimum net radiation.

In the modeled data the maximum temperature was modeled at 14.00hrs and the minimum was modeled at 3.00hrs. In the observed data the maximum temperature was recorded at 16.00hrs and the minimum temperature at 05.00hrs. The delayed peak in temperature in observed data. Similarly the variances for 24hrs period for the maximum temperature day in rural environment were observed and these are:

Rural environment: Modeled data

Table: 21 Surface temperature and time of days with maximum temperatures in rural environment (Modeled data)

	Surface Temperature and time		Wind speeds
	Maximum temp/Time	Minimum temp /Time	
Day one	33.09 º C- 12.00hrs	9.74 º C- 4.00hrs	3.67 m/s
Day two	22.99 º C- 12.00hrs	10.19ºC -4.00hrs	7.32 m/s
Day three	19.18 º C- 12.00hrs	10.37 º C- 4.00hrs	11.01 m/s

The maximum temperature for rural-modeled data is at 12.00hrs with temperature at 33.09ºC. The wind speed was 3.67m/s for that particular day. The minimum temperature is 9.74 at 4.00hrs. With varying wind speeds the same trend is been observed. The maximum temperature for day two and day three is at 12.00hrs and the minimum temperature is observed at 4.00hrs in the morning. With surface temperatures of 22.99ºC and 19.18ºC respectively. The decrease in temperature after mid day the short wave radiation takes place and the effects are seen in the temperature drop as seen in Table: 21.

Rural environment: Observed data

Table: 22 Surface temperature and time of days with maximum temperatures in rural environment (Observed data)

	Air Temperature and time		Wind speeds
	Maximum temp/Time	Minimum temp /Time	
Day one	16.46 º C- 16.00hrs	11.09 º C- 6.00hrs	4.6 m/s/4.33m/s

The 24 hr variance in the observed data that are shown in the Table: 22 for the rural-observed data. Where the maximum air temperature was 16.46ºC at 16.00hrs and the minimum air temperature was 11.09ºC at 06.00hrs in the morning. This maximum air temperature of 16.46ºC was observed with the maximum wind speed on that day.4.6 m/s

The long wave radiation patterns in rural environments are similar to that of the urban environments where the warmest part of the day is approximately at 12.00hrs. The rural short wave radiation took place an hour before the sunrise at 4.00hrs and one hour before sunset at 20.00hrs. This difference in surface and air temperature can be explained by the fact that modeled data is in surface temperature and the observed data is in air temperature.

In summary, modeled data successfully demonstrated that wind speeds and roughness lengths altered surface temperature inversely in Greater Manchester.

5.4 Model output verification

In order to verify the findings of the model output, observed data from Meteorology office, UK was used for comparison. The results of the modelled output in the study were surface temperatures. However, the observed data used for comparison between modelled data and observed data were in air temperature. Therefore it is important to understand the inter-relation between air and surface temperatures.

Air and surface temperature regulation

Even though air temperature is a relatively simple indicator of the sensible heat and thermal comfort of the urban inhabitants it is highly vulnerable to outdoor disruption by factors such as wind speeds, wind direction, humidity, radiation etc. (Brown and Gillespie, 1995) Several attempts at modeling air temperatures have been comparatively less successful given the uncertainties involved. Therefore most studies attempt to model surface temperature. (Whitford et al., 2001)

Air temperature is influenced by the intensity of the Sun's energy that strikes the Earth's surface. The amount of radiant heat transfer from the sun to the Earth is known as short wave, which makes the ambient air- hot. Some of this constant flow of radiant short wave energy that the Earth receives is radiated back to space. This is known as long wave energy. To keep temperatures stable it is important that a balance is maintained between the short wave and long wave radiation exchanges. This heat exchange process occurs primarily in the boundary layer and is seen in the early hours of the day when the daily heating of the surfaces begin. The energy flow from the Sun to the Earth varies seasonally on a daily basis as and is evident from the rise and fall in surface and air temperatures. (Seinfeld et al., 2006)

During the day, if the flow of short-wave radiation absorbed exceeds the long -wave energy emitted the surface temperature increases. What does not leave the Earth’s surface is then stored in the surfaces of the built environment in small volumes. This retained heat moves vertically by *advection* (convection and conduction) with air movement from one layer to another. The air in contact with the surface is usually warmer than the air above it. This vertical motion occurs when the warm surface air is lifted into the atmosphere and the cold air above sinks (Seinfeld et al., 2006). Heat is lost to the upper atmosphere by vertical mixing by sensible heat transfer to the air above. As this is a slow process there is a time lag before distant air gets heated. Therefore, air temperature is comparatively lower than surface temperature.

This is also evident form the study findings where the observed data were comparatively lower than model estimates and are shown in Table: 24. The heat transfer from surface to air continues as long as the surface temperature is higher than the air above it. The delay in the occurrence of the maximum air temperature in observed data (16.00hrs local time) could be attributed to this slow gradual heating of the air by convection transfer from the surface below.

Thus, the correlation between thermal surface properties, atmospheric mixing, and the mean wind velocity in urban areas mainly explains high surface temperatures and comparatively lower air temperatures. (Stoll and Brazel, 1992)

Even though same spatial and temporal patterns are seen in air and surface temperatures they do not correspond exactly. (Arnfield, 2003) Air temperature may be same as surface temperature due to mixing of the air. (Gill, 2006) However, the surface temperature varies widely. These variances are site specific and each city has its own profile for air-surface temperatures. Therefore, surface temperatures are more relevant when studying canopy microclimates. The Table: 23 summarize the observed differences in air and surface temperatures attributed to urban environment in Greater Manchester. The difference in air and surface temperature for high-density residential areas is under 2°C.

Table: 23 Data for urban environment showing difference in air and surface temperatures.

Urban Condition	Surface Temperature	Air Temperature
Improved farmland	13.58 °C	12.26 °C
High density residential area	14.22 °C	13.10 °C

The Table: 24 summarize the model surface temperature output data comparison with the recorded observed data for air temperatures.

Table: 24 Modeled data output vs. observed data with maximum daily temperatures

Condition	Model Temperature (wind speed)	Time	MET Temperature (Wind Speed)	Time
Urban	31.62°C (3.67m/s)	14.00hrs	24.93°C (7.33 m/s)	16.00hrs
Rural	33.09 °C (3.67 m/s)	14.00hrs	16.46° C (7.66 m/s)	13.00hrs

The surface and air temperature differences are more pronounced in urban settings than the rural for two reasons. First, because the atmosphere is altered by emissions and pollutants that do not allow averaging of incoming energy from the atmosphere and outgoing energy from the Earth. Secondly, built environments are poor reflectors and excellent energy absorbers. Low *albedo* further enhances nighttime temperature rise. To further add to the already rising temperatures in urban environment long wave energy transfer process itself generates energy as a by-product, which gets added to the long wave radiation. This explains the high temperature in urban environments. In the night time case of urban heat islands, surface –air temperature differences is expected to be minimum as winds increase, due to mixing and disruption of any surface based inversion layer with relatively close coupling of the surface and air temperatures reduces micro scale advection. (Dousset, 1989)

In summary, both air and surface temperatures were higher in urban environment. Although, wind speeds affected the temperatures in urban and rural environment similarly increasing wind speeds rapidly decreased rural temperatures to a significantly low value. Therefore the difference in urban –rural temperatures is more pronounced as also seen in Figure 24. This means that the wind would affect urban heat islands in Greater Manchester.

The model was partly successful in estimating surface temperatures at fixed parameter inputs. The modeled data for urban surface temperature was near accurate. This is satisfactory as the model was essentially to study urban environments. The model estimates for rural surface temperature were significantly different from real data. The reasons for this are the lag and lead between the modeled data and the observed data. First, this may be because surface temperatures are generally higher than air temperatures. Second, this could result from the model run assumption in the case study that the building heights of Greater Manchester is 2m, where in reality there are taller buildings. The modeled data is also leading ahead in time due to its various input parameters. Third, may also be attributed to the complexities of natural climatic conditions on that particular day, which are rather difficult to be modeled accurately.

Some of the other drawbacks identified in the study and the model itself that may have contributed to the discrepancies in observations are:

5.5 Model and Study Limitations

The Tso model has multiple variables and many of them were kept constant for the purpose of this study. The inputs for this study were:

Model Limitations

- Modeled data output is for surface temperature, which limits assessment since most meteorological data is available for air temperature as against surface temperatures.
- Tso model is built for urban energy balance and not for rural environments.

Study Limitations

- Roughness lengths were constant while running the model for varying wind speeds for both urban and rural environments.
- Wind speeds were kept constant while running the model for varying roughness lengths.
- Evaporative factor was kept constant for urban morphologies in urban and rural environments. There were no variations in urban or rural morphology types.
- It assumes that building mass is either high-density residential area or an unimproved farmland. In reality the land use would be different in urban morphologies.

- It assumes that all buildings are 2 floor brick houses in Greater Manchester however in reality this would be high-rise building.

5.6 Implications for future research

Overall the model is sensitive to wind speeds. Duplicating efforts at multiple locations and across cities will provide better insight into model functioning as well as improve understanding of wind speeds and roughness length effects on urban heat islands effect on a case-to-case basis and allow drawing generalizations if any. Continuing model testing will generate evidence for urban planners and policy makers to better mitigate effects of urban heat island.

To improve understanding of air and surface temperature differences, coupled models of surface and atmospheric processes are required. These models however are more likely to work well only under restricted lab atmospheric conditions and surface properties. Satellite observations are increasingly advocated to understand the relationship between surface and air temperatures. (Voogt, 2003)

The study enables us to determine the role of urban canopy and boundary layer climates in the rise in temperatures in urban areas. Modification of urban areas for development determines roughness lengths in a given city. It is clear that the wind speeds depend on roughness lengths especially in the urban built environment. It is only pragmatic to consider these factors in urban planning. Given that most climatic conditions are largely unpredictable, use of various climate models for simulating future climate systems based on current indicators is an essential step in anticipating future risks. This also helps guide mitigation plans for local or regional processes and helps reduce unintended effects of development on the environment. As Rene Dubos, advisor to the United Nations Conference on the Human Environment in 1972 puts it "*Think globally, Act locally*".

Chapter 6
Conclusion

It may be concluded that

- Wind effects and roughness lengths inversely affect surface temperatures in urban environments.
- The study has investigated the interrelationships between the various factors that affect wind speeds and roughness lengths in urban environments.
- Wind speeds affected temperatures in both rural and urban areas. However, increasing wind speeds rapidly decrease rural temperatures to a significantly low value hence making the difference in urban –rural temperatures was more pronounced. This means that the wind would affect urban heat islands in Greater Manchester
- However, this needs to be verified with larger observed data over periods of time.
- Tso energy balance model is adapted for urban environment and provides necessary opportunity to investigate urban heat island effects.
- Modeling provides a pragmatic opportunity to simulate risks from rising temperatures and other related phenomenon's in urban environments and continued research in the field is mandated.

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